Fermi National Accelerator Laboratory

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Upgrading the TEVATRON to a 1 TeV on 1 TeV pp Collider

L.C. Teng
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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The major items necessary for this upgrading are the following:

1) Remove the 150 GeV main ring (MR) from the main-ring tunnel. In principle, this is necessary only at interaction regions (IR) to make room for the detectors. This was done with the overpasses at B0 and D0. Elsewhere, the MR needs only to be moved away from its present position atop the Tevatron collider ring to make room for the second ring and can remain in the tunnel if desired.

2) Lengthen the straight sections of the Tevatron ring (collider ring one, CR1) by replacing a number of the 4.4-T dipoles at the ends of the arcs by higher field dipoles. For the present study we shall adopt for the higher field dipoles, 6.6-T dipoles similar to the SSC dipoles but only 20 ft in length.

3) Add the second collider ring (CR2) which has the same dipole arrangement, hence geometry, as CR1 (except for the polarity).

4) Form the IR insertions. This includes investigations of:

a. Geometry - we assume the over/under geometry with vertical crossings.

b. Low-β^* optics - adequate space must be allowed for strong quadrupoles to create low-β's at the interaction points (IP's). We assume that $\beta^* \simeq$ 1m is desired.

c. Dispersion suppressing - the quadrupoles at the ends of the arcs can be tuned to give zero dispersion in the straight sections.

5) Finally, one may want to consider the possibility of continuing the operation of the $\bar{p}$-source and the $\bar{p}p$ colliding mode.

Since the feasibility of forming the IR insertion is a more crucial question than that of relocating the MR, we shall start our investigation there.

Formation of the IR Insertion

We assume here that the MR has been removed from the tunnel.

A. Lengthening the Straight Section

To lengthen a straight section in CR1 we replace a number of the 4.4-T dipoles at the ends of the arcs on either side by 6.6-T dipoles yielding the same bending angles. We assume the 6.6-T dipoles to have the same length, 20 ft, as the replaced 4.4-T dipoles, and for clarity of illustration, we shall ignore the missing dipole at station 48. It is obvious that by proper shortening and adjusting the longitudinal position of the 6.6-T dipole at station 48 one can always make the modified orbit to fit exactly. Also, to facilitate the more-or-less generic discussion here we assume a featureless approximate Tevatron lattice with exact 6-fold symmetry and each sector composed of a 16 1/2 cell "arc" of length 16.5 x 59.4868m = 981.5322m and a straight section of length 65.66535m. The same geometry is later assumed also for the MR.

Fig. 1 shows the orbit geometry change. We replace 12 4.4-T dipoles by 8 6.6-T dipoles at each end (e.g. between A-46 and B-14 for straight section B). The cell length and the quadrupoles are not changed. The average bending radius for cells with 4.4-T dipoles and 6.6-T dipoles, and the length change and lateral displacement of the straight section are tabulated in Table 1 below.

Table 1 Straight Section Lengthening Parameters

	4.4-T dipole	6.6-T dipole
Cell length	59.5 m	59.5 m
Bend angle	64.9 mrad	97.4 mrad
Average cell radius	916 m	610.7 m
No. of dipoles replaced	-24	16
Straight section length	65.7 m	125.1 m
Lateral displacement	-	1.448 m (inward)
Replaced arc length	3 x 59.5 m	2 x 59.5 m
Total length (46 to 14)	244.126 m	244.032 m

Each sector is shortened by 0.094m and the total circumference is shortened by 0.564m to 6282.6213m and the rf frequency is increased by $\Delta f/f = 9 \times 10^{-5}$. We shall see later how this slight frequency shift can be easily taken care of.

The inward lateral parallel displacement of 1.448m brings the straight section orbit to the inner radius side of the tunnel ~ 3 1/2 ft from the inner wall. This is a convenient location. Of course, the tunnel in the neighborhood of the IP must be enlarged to accommodate the detector.

Since the width of the tunnel does allow a larger lateral orbit displacement one can, in principle, replace more 4.4-T dipoles by 6.6-T dipoles to further lengthen the straight sections. But we shall see below that the 125m straight section length is already adequate.

A total of 6 x 16 x 20 ft = 1920 ft = 585 m of 6.6-T dipoles is needed. Using the unit cost of the SSC dipole of ~ \$5.5k/m, this amounts to ~ \$3M.

B. Adding the Second Collider Ring CR2

We assume that CR2 has exactly the same lattice as CR1 being composed of both 4.4-T and 6.6-T dipoles, and is installed on top of CR1. The separation between CR1 and CR2 orbits depends on the height of the magnets, in particular the height of the 6.6-T dipoles. We assume an orbit separation of 0.6m so that we can use, without modification, the SSC dipole which has a 0.6m diameter circular outer dimension, although since the beam aperture is off-center in this dipole it should be possible by a simple rearrangement to reduce the necessary orbit separation.

The cost of the second collider ring should be about the same as that of the Tevatron ring, namely about \$60M.

C. Design of the IR Insertion

The IR insertion conceived is shown in Fig. 2. The dimensions given are only first order guesses and are not to be considered as real design parameters. Going away from the IP where the two beams collide nearly head-on (see further discussion below) one encounters in succession the following sections:

1) A 7-m drift space to accommodate the detector. This length is taken to be the same as that of the Tevatron collider at B0. Independent of any argument for the optimal choice of the drift space this will make it straight forward to use the CDF on the pp collider.

2) A triplet of strong quadrupoles used commonly by both beams to yield a low β^* of ~ 1m at the IP. The total length of the triplet is conservatively taken to be 12m. For the Tevatron collider this distance is ~ 18m. This is rather long because the quadrupoles used are rather weak, less than half the strength of the SSC quadrupoles, and the very short and already installed straight section forced an inefficient design. The same distance scaled (as $p^{1/2}$) from the SSC is only ~ 9m.

3) A vertical beam separating dipole used commonly by both beams with field x length = (6.6T) x (3.5m) which imparts an angular separation between the beams of $\pm$ 6.9 mrad. After traversing a distance of 43m to the end of the straight section, the beams are separated by the desired $\pm$ 0.3m.

At the exit of the beam separating dipole the beams are separated by $\pm$ 12mm. Thus, the "good"-field aperture of this dipole should be larger than that of the 6.6-T dipoles in the ring by that much.

4) In the first 10m of the 43m beam separating length, the separation between the beams are too large for the beams to go through the same magnet aperture and too small for the beams to go in separate magnets. But beyond 10m the beam separation gets > 14 cm which is adequate for the beams to separately go through the apertures of staggeredly placed thin top-and-bottom-yoke quadrupoles having overall vertical dimensions of < 28 cm. We estimate that 3 or 4 quadrupoles are needed for each beam, located between 10m and 43m from the common dipole to match the beam optics to those at the arc end.

5) To bend the vertically separating beams back to the horizontal plane we need to roll the 6.6-T dipoles at the end of the arc by a small angle. If the first 4 dipoles are used, to bend the beam 6.9 mrad the roll angle should be 160 mrad. In addition to creating the vertical bending this roll will also reduce the total horizontal bend-angle of these dipoles by 0.55 mrad which, although small, should be taken into account or compensated for in the design.

The first 3 or 4 cell quadrupoles at the end of the arc should be adjusted in strength to yield zero dispersion in the straight section. So doing, we are actually using the arc-cell dipoles and quadrupoles beyond the ends of the straight section to form the crossing geometry and the zero dispersion. Thus, these magnets should be considered as part of the IR insertion, and the total length of the insertion is actually a few cell lengths longer than the 125 m of the straight section. The details of the insertion will take considerably more time and effort to work out, but are not vital for the discussion here.

Since the beams collide at a small but finite angle (see below), to keep the IR insertion exactly antisymmetric (horizontal optics before the IP is mirror reflection of the vertical optics after the IP, and vice versa) the beams must cross over and the two rings must interchange at the IP. We shall see later that straight sections A and F are utility straight sections without cross-over, and the other 4 straight sections B, C, D and E can be used as IR's. Because of the cross-over geometry, there can be either 2 or 4 IR's. We assume that one starts with only 2 IR's at the diametrically opposite straight sections B and E, and add 2 more (C and D) in the future when the demand arises.

Relocation of the Main Ring

Many different possibilities were explored. The most promising is the following modified version of the original proposal by Mike May.

A. Geometry, Optics and Acceleration

As shown in Fig. 3 the section of MR between stations E49 and A11 (sector F plus straight sections A and F) remains in the present tunnel. The rest of the MR is moved into a new shorter tunnel by the use of full strength MR dipoles at 150 GeV. The relocated main ring (RMR) has an oval geometry with two-fold symmetry and 4 straight sections labelled A, C, D and F. The large radius side-arcs are denoted as sectors C and F (coinciding with the old sector F which remains in the old tunnel) and the small radius end arcs are denoted as sectors A and D. Straight sections A and F of the collider rings are, then, utility straight sections; and straight sections B, C, D and E can be used as IR straight sections.

The lattice of RMR sector C is identical to that of sector F with missing dipoles at stations 17 and 48. Sector D is identical to sector A, each having 12 1/2 cells and a bend-angle of $2\pi/3$. With the 4th dipole from straight section A (and D) omitted to make room for the counterclockwise extraction kicker, the total number of dipoles in sector A (or D) is 99. The straight sections are lengthened slightly to give the proper rf harmonic number to match to the rf frequency of the collider rings. Cell quadrupoles have about the same strength and the phase-advance per cell is about the same as in the present MR. The major parameters of RMR are given in Table 2.

Table 2 Parameters of RMR

Sector A (or D)	
No. of cells	12 1/2
Arc length	743.585m
No. of dipoles	99
Total bend-angle	$2\pi/3$
Dipole bending radius	286.951m
Dipole field at 150 GeV	1.755T
Orbit sagitta in dipole	16.05mm
Sector F (or C)	
No. of cells	16 1/2
Arc length	981.532m
No. of dipoles	129
Total bend-angle	$\pi/3$
Dipole bending radius	747.812m
Dipole field at 150 GeV	0.673T
Orbit sagitta in dipole	6.16mm
Straight section length	66.005m
Circumference of ring	3714.254m
RF harmonic number	658
Betatron tune	~ 12
Maximum β	~ 110m
Maximum dispersion D	~ 5m

One notes from Table 2 that the rf wave length, $\beta\lambda$ = circumference per harmonic number = 5.64476m is matched to that of the colliders (6282.621m/1113). One notes also that although the orbit sagitta in the strong dipoles in sectors A and D is almost three time that in the weak dipoles, it is still quite tolerable.

The materials cost of the RMR is mainly that of the new tunnel which is ~ 2600m in length. Using a unit cost of ~ \$4.5k/m we get a total of ~ \$12M. The manpower cost to reconstitute the MR into the RMR is difficult to estimate but is expected to be substantial.

B. Beam Transfers

The RMR should be capable of bipolar operation to accelerate proton beams in either direction. The transfer of beams from the RMR to the collider rings CR1 and CR2 can be carried out in straight section A. This is made especially easy by the lengthening of the collider straight sections. Fig. 4 shows the geometry of the beam transfer lines.

For the clockwise transfer from RMR to CR1 the 150 GeV beam in RMR is first kicked down-and-left (looking along the beam), namely in the direction toward the CR1 orbit, by a kicker located at F48, across a ramped current-septum, ES1, located at the beginning of straight section A. The current septum with $B\ell$ = 0.85T x 4m deflects the beam also down-and-left by 6.7 mrad. After travelling ~ 90m the deflected beam arrives at the CR1 orbit near the end of straight section A where it is deflected to parallel the orbit by a similar but reversed current septum, IS1. Further downstream where the beam crosses the CR1 orbit, an on-orbit kicker kicks the beam onto the orbit. Note that here we use both the kicker and the septum in a tilted direction, neither horizontal nor vertical. This arrangement optimizes the efficiency and reduces the required strengths of these devices. Thin side-yoke quadrupoles can be placed in the middle ~ 50m of the ~ 90m beam transport line for optics and dispersion matching.

The counterclockwise transfer of the beam from RMR to CR2 is accomplished in an analogous manner, but deflecting the beam up-and-left. In all the discussions here and in Fig. 4 we have ignored the matching quadrupoles in the straight sections. Since the straight section lengths are ample and the design of the matching quadrupole arrangement is very flexible, there should not be any difficulty in avoiding space conflicts between the current septa and the matching quadrupoles.

Injection of the 8 GeV beam from the Booster to the RMR in both directions can be carried out using existing beam lines or, at least, existing beam-line tunnels. The clockwise injection is into the RMR straight section A. Since the current septa for RMR-to-collider beam transfers are only 4m long and are located at the ends, the middle 50m of the straight section A is clear and free, especially if approached from the inner radius side. There should not be any difficulty injecting the 8 GeV beam there.

For counterclockwise injection we use the beam extracted from the Booster at long straight section 3 and follow the p̄-source beam lines AP4 (booster test beam line) and AP3 (accumulator to MR line) to inject into the RMR at F17. Again, no civil construction is needed.

The circumferences of the modified collder rings CR1 and CR2 and the RMR are designed for an rf frequency which is $\Delta f/f \simeq 9 \times 10^{-5}$ higher than that on the central orbit of the Booster. The requires that the accelerated beam be extracted from the Booster not from the central orbit but from an orbit which is ~ 1.3 cm max. on the inner radius side. The present radial-position- and phase-lock system for the beam transfer between Booster and MR can be modified to accomplish this.

C. p̄ Operation, Fixed Target Operation, Beam Abort Systems

With this RMR the entire p̄-source facility and the beam lines to and from F17 are left intact (except for minor shifts of the MR end of the beam lines to follow the move of the F sector away from the position on top of CR1). Thus, the whole p̄ operation can continue unchanged and with CR1 as the p̄p colliding ring. The geometry of the IR insertions is such that p̄p collisions will occur exactly at the IP's of pp so that the detectors can be used directly without any modification or realignment.

Straight sections F of the colliders are essentially free, except for some 12m space for 4 rf cavities in each ring. It should be possible to accommodate some high efficiency beam abort systems in these straight sections.

If fixed target operation is still desired one can move the RMR-to-collider beam transports to straight section F and keep the extracted beam line emerging from CR1 straight section A intact. To do this, one must remove first the RMR rf system to, say, straight section D and then the collider beam abort systems to some other straight section(s). The abort system of CR2 can be moved to straight section A which is now totally free, and it may be possible to combine the abort system of CR1 with the beam extraction system also in straight section A. Otherwise, one may have to use one of the collider straight sections earmarked for IR, leaving only three maximum possible IR's.

Cost and Performance

A. Cost

We list only the major items of the upgrade and their estimated costs in round M\$. (Most of the unit costs were provided by Rich Orr).

		M\$
Second collider ring CR2		60
6.6-T dipoles for CR1		3
Two IR insertions		10
New RMR tunnel		12
Manpower		10
	Total	100

The simple arithmetic of totaling was deliberately done in rough approximation to indicate the very crudeness of the guesstimate. We note only that a fairly good cost estimate can be made with some effort because all components of the project are fairly well defined.

B. Performance

1. Collision angle

The beam bunches must collide at a small but finite angle so that at the neighboring crossing points the bunches are separated. However, the collision angle θ must be kept at a minimum, otherwise the luminosity will suffer. These conditions can be expressed as

$$\frac{\sigma^*}{\beta^*}\left(1 + \frac{\beta^{*2}}{\ell^2}\right)^{1/2} > \theta > \frac{\sigma^*}{\beta^*}\left(1 + \frac{\beta^{*2}}{L^2}\right)^{1/2}$$

where

β^* = low β at IP

σ^* = rms beam width at IP

ℓ = rms bunch length

L = distance to neighboring crossing point

If all rf bunches are filled

$L = 2.8\text{m},$

and if we get a 95% normalized emittance at 1 TeV of $\epsilon_n = 10\ \pi$ mm-mrad and

$\beta^* = 1\text{m}$

$$\sigma^* = \left(\frac{\epsilon_n}{6\pi\gamma\beta^*}\right)^{1/2} = 40\ \mu\text{m}$$

We also have, approximately

$$\ell = 0.25\text{m}.$$

This, then, gives

$$165\ \mu\text{rad} > \theta > 42\ \mu\text{rad}$$

It is more important that the bunches are sufficiently separated at the neighboring crossing points to avoid detrimental long range beam-beam effects, therefore we take a θ value close to the upper limit,

$$\theta = 150\ \mu\text{rad}.$$

Then, at the neighboring crossing points

$$\sigma = 120\ \mu\text{m}, \qquad \text{separation} = 420\ \mu\text{m},$$

namely that the beam bunches are separated almost by 4σ; and at the rms bunch end

$$\sigma = 41\ \mu\text{m}, \qquad \text{separation} = 38\ \mu\text{m},$$

showing that the beam separation is only ~ 0.9σ there and that the luminosity reduction is minor.

If we get $N = 5 \times 10^{10}$ protons/bunch, the luminosity is

$$\mathscr{L} = f \frac{N^2}{6\pi\sigma^{*2}} = 4.5 \times 10^{32} cm^{-2} sec^{-1}$$

and the beam-beam tune shift is

$$\xi = \frac{r_o}{\gamma\beta^*} \frac{N}{6\pi\sigma^{*2}} = 0.0024$$

where

$$r_o = \frac{e^2}{mc^2} = 1.535 \times 10^{-18} m = \text{classical proton radius}$$

Admittingly these are optimistic numbers, but realistically one should be able to get a luminosity of $1 \times 10^{32} cm^{-2} sec^{-1}$.

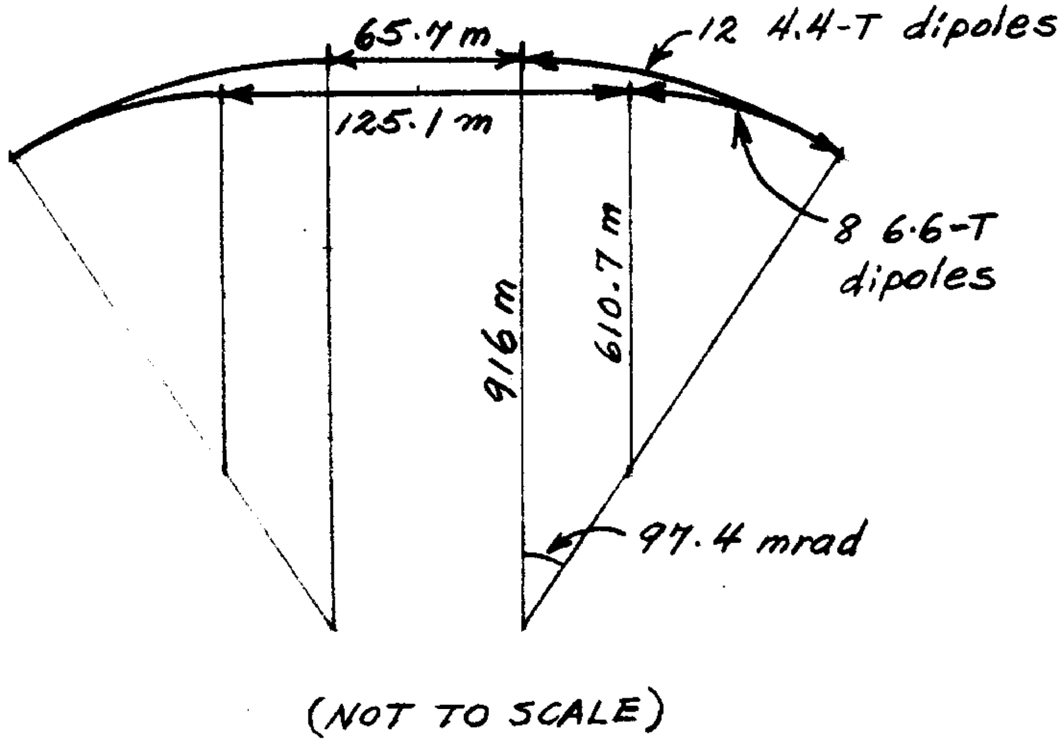


Figure 1. Geometry of the straight section before and after lengthening.

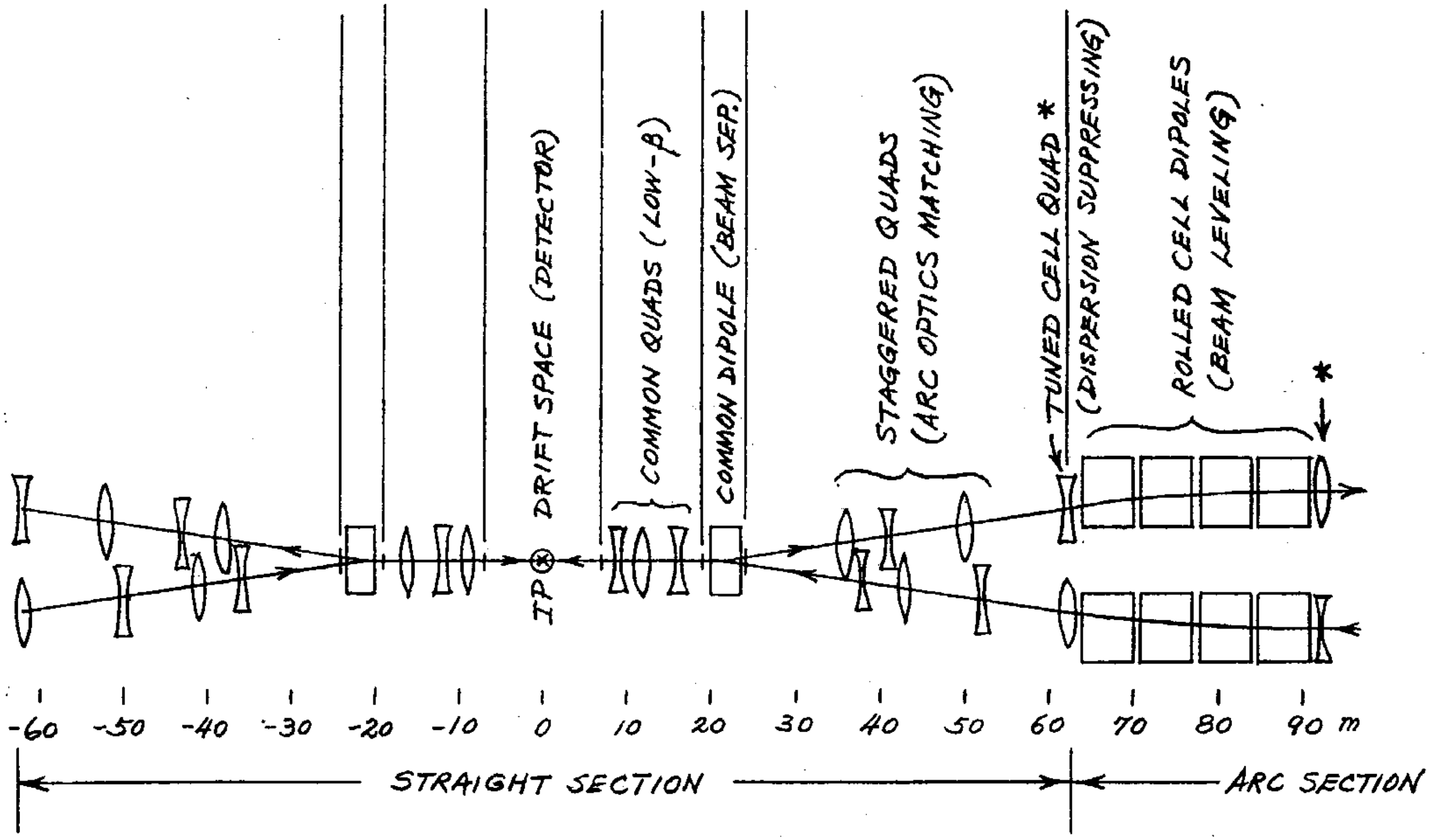
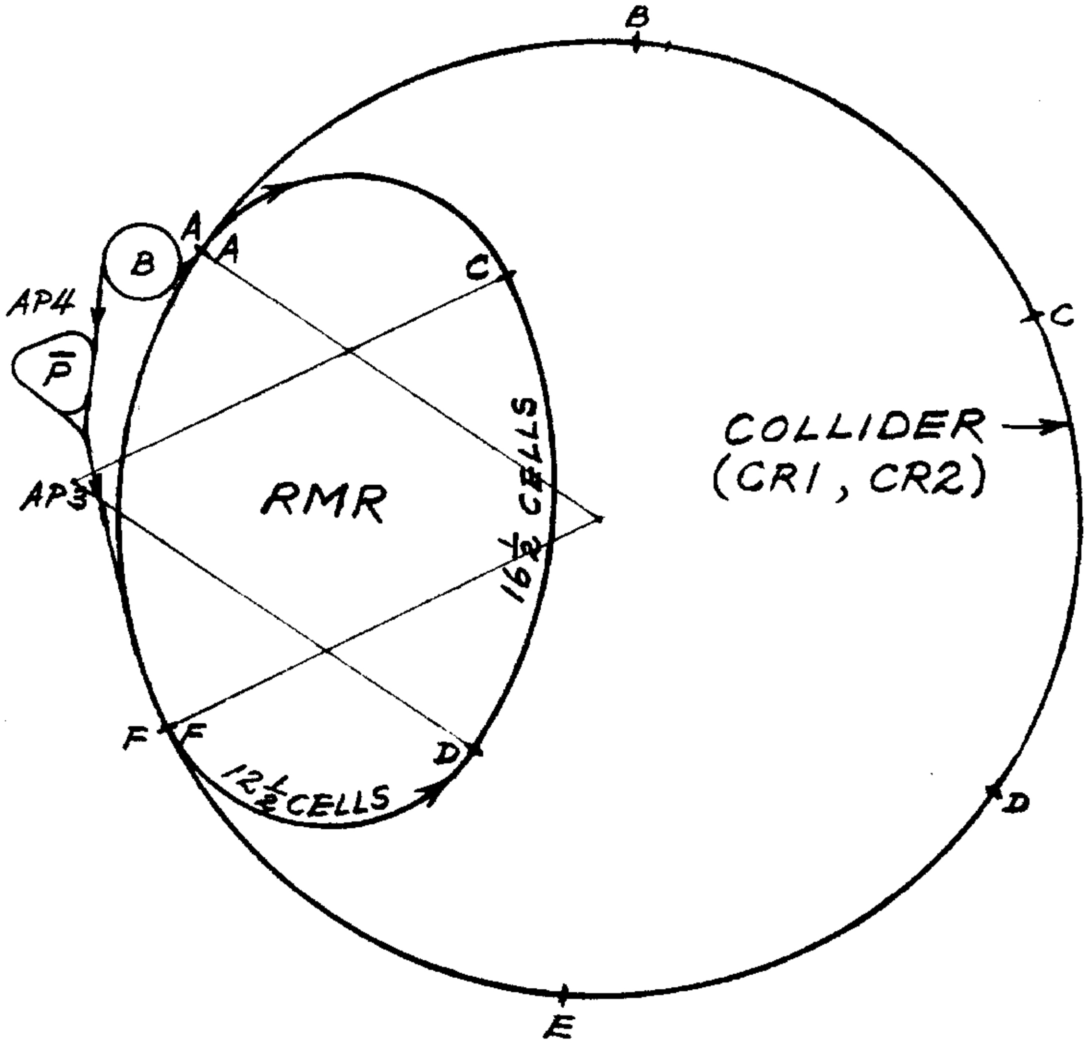


Figure 2. The interaction region insertion



(STRAIGHT SECTIONS OMITTED)

Figure 3. Geometry of the Reconstituted Main Ring (RMR) and the Collider Rings (CR1, CR2).

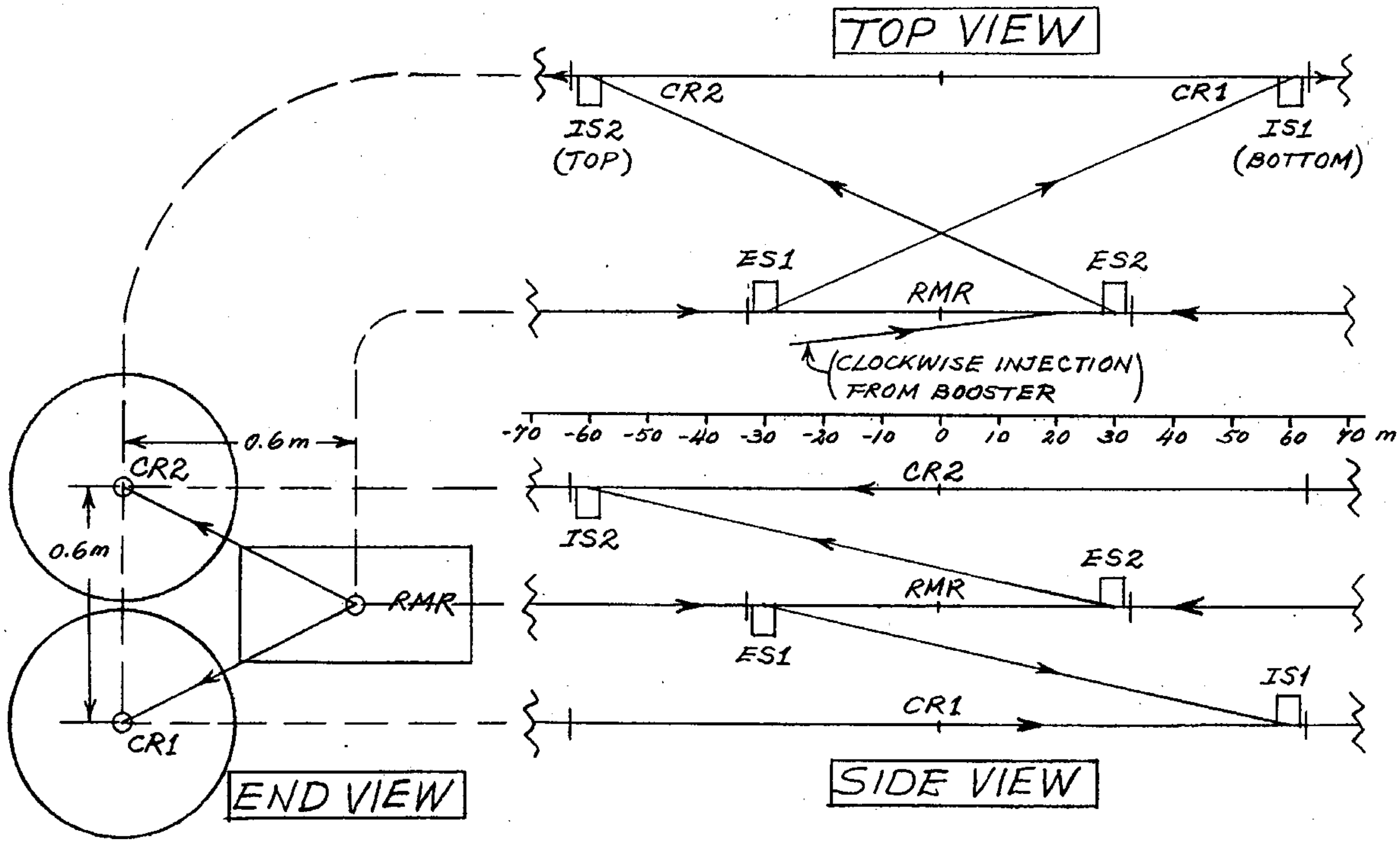


Figure 4. Geometry of the beam transfer lines between RMR and CR1/CR2.